TEMPORAL EFFECTS OF MECHANICAL TREATMENT ON WINTER MOOSE BROWSE IN SOUTH-CENTRAL ALASKA

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ABSTRACT: Sites containing winter browse species utilized by moose on the Copper River Delta of south-central Alaska were mechanically treated (hydraulic-axed) to counteract possible earthquake-related increases in less-preferred forage species, and to measure treatment effects on biomass, height, nutritional quality (crude protein, lignin, and tannin), utilization, and snow burial on preferred (willow [*Salix* spp.]) and less-preferred forage species (sweetgale [*Myrica gale*], cottonwood [*Populus trichocarpa*], and alder [*Alnus viridis sinuata*]) within 3 winter scenarios (mild, moderate, and severe). Sites were treated in 4 winters (1990–1992, 2008, 2010, and 2012) within 5 stand types in 20 sites varying from 0.9–63.4 ha. We found few significant differences in biomass, height, nutritional quality, utilization, and snow burial relative to controls. However, our ability to detect differences may have been limited by sample size (n = 1–9), as visual comparison suggests hydraulic-axing may be an effective method for increasing willow biomass while reducing alder biomass without influencing nutritional quality. However, because treated willows were shorter than untreated willows, treatment may result in less preferred forage for moose in severe winters with deep snow. Our results have implications for habitat management of moose but further research is needed to determine incremental and long-term effects of treatment on willow growth and productivity.

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Since many deer species in North America rely on early-successional forage, habitat management efforts commonly delay forest succession through mechanical treatment via shearing, crushing, or axing of overstory vegetation (Scotter 1980, Hundertmark et al. 1990, Renecker and Schwartz 1997, Thompson and Stewart 1997, Suring and Sterne 1998). Mechanical treatment (hydraulic-axing) was applied on a limited scale to increase availability of preferred winter forage for an Alaskan moose (*Alces alces gigas*) population on the Copper River Delta (CRD, Stephenson et al. 1998), the location of this study (Fig. 1).

Moose were introduced to the CRD from 1949–1958 to establish a harvestable population, having likely been excluded by topography (MacCracken et al. 1997). With a potential range encompassing >54,000 ha, the more managed and hunted western subpopulation has since grown to >600 animals (C. Westing, Alaska Department of Fish and Game, unpublished data). However, intense winter winds through the Copper River canyon, variable snow depths, and snow drifting can restrict winter range access to 4,800–12,900 ha (MacCracken et al. 1997, Stephenson et al. 2006). This seasonal effect constrains accessible browse and has

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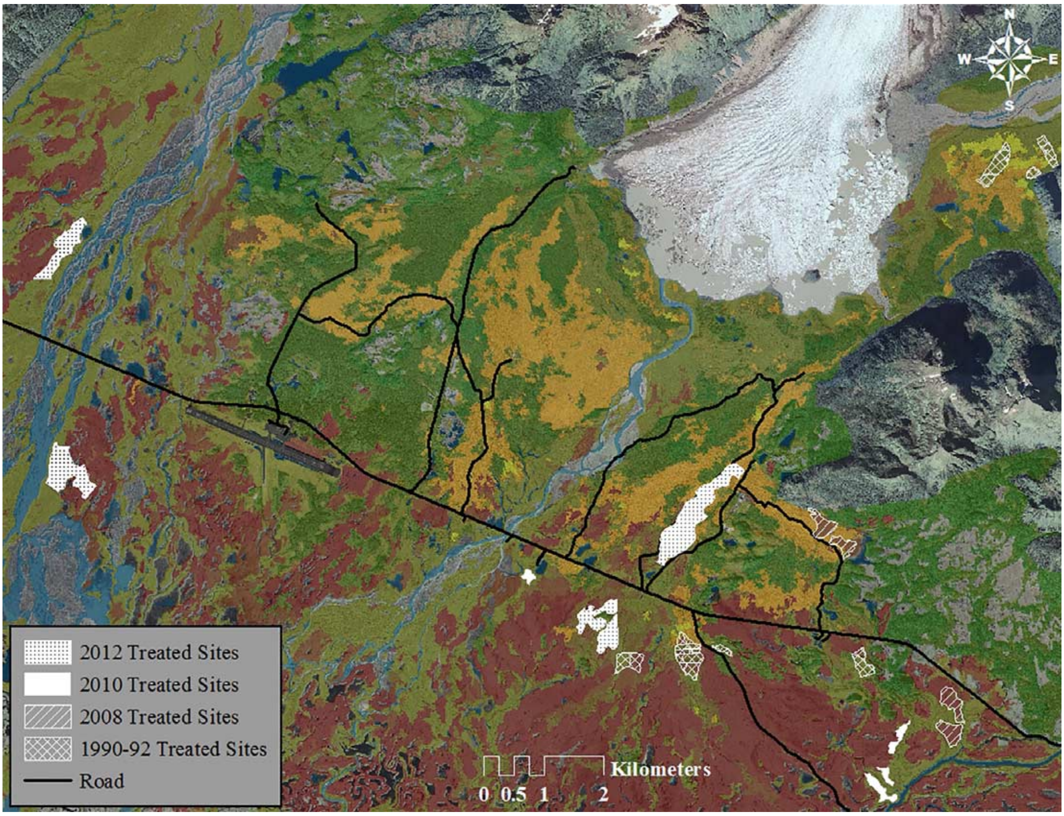


Fig. 1. Sites mechanically-treated (hydraulic-axed) in 1990–1992, 2008, 2010, and 2012 on the west Copper River Delta of south-central Alaska to improve the availability of willow forage for wintering moose.

historically been thought to limit adult moose survival (Regelin et al. 1985, Schwartz et al. 1988, MacCracken et al. 1997). Furthermore, a 9.2 magnitude earthquake in 1964 uplifted the area by 1.0–4.0 m (Grantz et al. 1964, Ferrians 1966, Plafker 1969, Stover and Coffman 1993), initiating changes in hydrology, soil salinity, and vegetation, including an acceleration of succession in some stands to stages with increased production of less-preferred browse (Thilenius 1990, 2008).

Managers are concerned that the combined effects of winter range restrictions and earthquake-initiated vegetation changes might limit the performance or persistence of this locally important population (MacCracken et al. 1997, Stephenson et al. 2006). As a result, the USDA Forest Service Cordova Ranger Station initiated experimental treatments of moose habitat with hydraulic-axing machines (hereafter hydro-axing) which use rotary axes to cut down and splinter trees or shrubs up to 15 cm in diameter (Stephenson et al. 1998). Initial treatment plots were cut in 1990–1992, followed by additional plots in 2008, 2010, and 2012 (M. Burcham, USDA Forest Service Cordova Ranger District, personal communication, Stephenson et al. 1998). Because wintering CRD moose depend on 5 willow species (feltleaf willow, Barclays willow, undergreen willow, Hookers willow, and Sitka willow [*S. alexensis, S. barclayi,* *S. commutata, S. hookeri, S. sitchensis,* respectively]), and only occasionally on black cottonwood (*Populus trichocarpa*), sweetgale (*Myrica gale*), and Sitka alder (*Alnus viridis sinuata*) (MacCracken et al. 1997), treatments have focused on increasing the willow component of stands. In the Kenai National Forest willows re-sprouted following mechanical treatment whereas mature red alder (*A. rubra*) experienced high mortality (Oldemeyer and Regelin 1980, Harrington 1984). Thus, most treatments on the CRD were sited on alder-dominated stands with remnant willow components, though spruce-cottonwood-, sweetgale-, and willow-dominated stands have also been treated (Table 1).

Stephenson et al. (1998) evaluated the success of the initial (1990–1992) treatments 1–3 years post-treatment, and found that alder mass generally declined and Sitka willow mass increased in treated sites. However, responses in biomass and utilization by other browse species varied by stand or were statistically precluded by sample size (Stephenson et al. 1998). In addition, mean height of browse in treated stands was often less than in controls, and snow-buried browse varied by location, treatment, and stand type. It was hypothesized that Sitka willow at full height (5 m) in alder- and willow-dominated stands would be especially important in winters with deep snow and heavy drifting. Therefore, it is possible that extensive treatment might increase the prevalence of shorter willows, coincidentally limiting browse available to moose in severe winters. However, hydro-axing effects in this system have not been studied beyond the first 3 years post-treatment.

Our objectives were to 1) evaluate species-specific and time-since-treatment responses of available biomass, height, nutritional quality, and moose utilization of winter browse species to hydro-axing 1, 3, 5, and 23 years post-treatment, and 2) estimate how biomass availability within treated sites varies with snow depth (winter severity). Our results will assist managers in assessing the relative benefits of hydro-axing to maintain willow availability for moose in a dynamic ecosystem.

Table 1. Characteristics of mechanically treated (hydraulic-axed) sites sampled (2012–2013) for moose browse species on the western region of the Copper River Delta, Alaska, including site age (years since treatment), control stand type, soil type, area (ha), and sampling replicates. Soil types include AST = alluvium and stream terrace deposits, OPN = glacial outwash plains, nonforested, and GM = undifferentiated glacial moraines (Davidson and Harnish 1978).

Age (yr)	Winter Treated	Control Stand Types	Soil Type	Replicates (n)	Size (ha)
1	2012–2013	Spruce-cottonwood	AST	1	57.9
		Alder	AST	2	23.9, 63.4
3	2010–2011	Alder	OPN	1	3.4
		Sweetgale	AST	3	8.0, 3.4, 5.7
5	2008–2009	Spruce-cottonwood	GM	2	10.7, 7.6
		Willow	AST	2	11.8, 10.5
22–23	1990–1991 & 1991–1992	Spruce-hemlock	OPN	2	0.9, 1.5
		Alder	AST/OPN	2	3.0, 2.2
		Alder-willow	AST	2	0.9, 4.9
		Willow	AST	1	1.5
		Sweetgale	OPN	2	2.6, 0.8

METHODS

Study Area

The CRD lies within the Chugach National Forest and is bordered by 3 glaciers, the Chugach Mountain Range, and the Gulf of Alaska (Fig. 1). As the largest continuous wetland in the Pacific Northwest, it extends 120 km along the coast and supports abundant early-successional browse in a moist, relatively mild climate, lengthy growing season, and continuous channel changes by glacial streams and the Copper River (Christensen 2000, Kesti et al. 2007, Thilenius 2008). Using a map derived from Satellite Pour l'Observation de la Terre (SPOT version 5 [SPOT5], 2011, Red Castle Resources, Inc.), we identified 7 stand types that produce winter moose forage: spruce-hemlock, spruce-cottonwood, cottonwood, alder, alder-willow, willow, and sweetgale (Viereck 1992). Spruce-hemlock, spruce-cottonwood, alder, and sweetgale can all form late-successional stands depending on hydrology, but alder-willow, willow, and sweetgale stands are generally considered early-successional (Boggs 2000).

Drainage and desalination resulting from the 1964 earthquake increased the distribution of spruce-hemlock and alder stands, while accelerating succession or increasing the composition of willow, alder, Sitka spruce (*Picea sitchensis*), and western hemlock (*Tsuga heterophylla*) within some stands (Boggs 2000, Stephenson et al. 2006, Thilenius 2008). Total winter snow depths range from 83.3–548.6 cm (1994–2013; ACRC 2014), and the area also receives substantial rainfall (annual mean of 236 cm), frequently interspersed within periods of snowfall (Kesti et al. 2007). This phenomenon varies with winter severity, which can significantly affect snow accumulation, drifting, and compaction. Thus, efforts to understand the complex interactions among snow depth, moose behavior, and browse availability are complicated and challenging.

Treatments and Data Collection

Prior to initial treatments, managers subjectively rated the suitability of potential treatment sites as high, medium, or low using factors of willow composition, encroachment by other woody species, and the level of understory organic matter (M. Burcham, USDA Forest Service Cordova Ranger District, unpublished data); only highly suitable sites were treated. Due to the logistical difficulty of moving heavy equipment through wetlands, treatment occurred during winters with sufficiently frozen ground, and sites were partially determined by road access. Managers refined their site selection techniques after the 1990–1992 treatments, selecting stands with the greatest potential for increased willow production. In total, the Forest Service treated approximately 300 ha from 1990–2012. Treatments were applied to 32 sites in 5 stand types varying from 0.9–63.4 ha in the east-central, mid-central, and north-central regions of the west Delta (Table 1; Fig. 1). All sites were unfenced and open (available) to moose.

We sampled sites in August–September 2012–2013 and April–May 2013 to capture pre-winter available biomass and over-winter utilization and nutrition, respectively. Because of logistical difficulties and differences in moose browsing pressure among sites, we selected 20 comparable sites treated in the east-central and mid-central region of the Delta (Table 1; Fig. 1). We randomized sampling plots in treated sites and untreated adjacent controls, categorizing each site by the current control stand type. Our study plots consisted of 3 random-start belt transects (1 × 10 m) separated by 5 m and running north, north, and east, respectively.

We estimated the forage biomass available to moose (total biomass of twigs with diameters ≤8.3 mm; g/stem) with basal diameter-mass regression equations (Table 2; MacCracken and Van Ballenberghe 1993, Stephenson et al.1998). At every 0.5 m along

Table 2. Regression equations used to estimate species-specific available biomass (g/stem) and biomass consumed (g/twig) by moose wintering on the Copper River Delta, Alaska, USA.

Browse Species	Time Since Treatment: 1 Year[a]	3 Years[a]	5 Years[b]	22–23 Years[b]	Untreated[c]	Consumption[c]
Cottonwood	$= \exp(-4.22)\ (BD^{2.85})$	$= 0.64\ (BD)$	$= 0.15\ (BD^{1.97})$	[g]–	$= 2.37\ (BD)$	$= 0.04\ (bD^{2.6})$
Alder	$= \exp(-3.89)\ (BD^{2.77})$	$= \exp(-2.45)\ (BD^{1.8})$	$= 0.03\ (BD^{2.58})$	$= 4.12\ (BD)$	$= 2.33\ (BD)$	[d]$= 0.03 + 0.06\ (bD^{2.5})$ or $= 0.34\ (bD^{4})$
Sitka willow	$= \exp(-3.16)\ (BD^{2.52})$	$= \exp(-0.93)\ (BD^{1.46})$	$= 0.13\ (BD^{2.02})$	$= 0.21\ (BD^{1.8})$	$= 11.07\ (\ln BD)$	$= 0.03 + 0.06\ (bD^{2.5})$
Barclay willow	[e,f]$= \exp(-3.50)\ (BD^{2.72})$	[f]$= 0.98\ (BD)$	$= 1.74\ (BD)$	$= 2.56\ (BD)$	[e]$= 0.14\ (BD^{1.93})$	$= 0.05 + 0.03\ (bD^{2.7})$
Hooker's willow	[e,f]$= \exp(-3.50)\ (BD^{2.72})$	[f]$= 0.98\ (BD)$	$= 0.11\ (BD^{2.09})$	$= 1.43\ (BD)$	[e]$= 0.18\ (BD^{1.80})$	$= 0.05 + 0.03\ (bD^{2.7})$
Undergreen willow	$= \exp(-3.12)\ (BD^{2.48})$	$= 0.56\ (BD)$	$= 1.51\ (BD)$	$= 1.40\ (BD)$	$= 0.55\ (BD)$	$= 0.05 + 0.03\ (bD^{2.7})$
Sweetgale	$= 0.12\ (BD)$	$= 0.22\ (BD)$	$= 1.26\ (BD)$	$= 1.70\ (BD)$	$= \exp(-3.33)\ (BD^{2.15})$	[d]$= 0.05 + 0.03\ (bD^{2.7})$ or $= 0.12\ (bD^{2})$

Available biomass and biomass consumed equations are derived from measurements of basal diameters (BD, mm) and bite diameters (bD, mm), respectively. Available biomass equations were developed in both mechanically-treated (hydraulic-axed) and untreated control sites. Treated site equations are presented according to their site age (time since treatment, as of sampling in 2012 & 2013).

[a]Developed by Stephenson et al. (1998).
[b]Developed by Smythe et al. (current).
[c]Developed by MacCracken and Van Ballenberghe (1993).
[d]Revised by Stephenson et al. (1998).
[e]Revised by Smythe et al. (current); negative added to coefficient.
[f]Separate equations were not developed for Hooker's and Barclay willows (Smythe unpublished).
[g]Sample size was insufficient to develop a regression equation.

the belt transects, we measured basal diameters (mm; above the moss layer) of the 3 stems closest to the transect line. Past research indicated that very large stem basal diameters (>60.0 mm) increased regression equation heteroskedasticity (MacCracken and Van Ballenberghe 1993). Thus, with such stems we instead measured a branch diameter and estimated how many equivalent branches were on the stem. Within the belt transects, we calculated stem density (stems/belt; stems/ha), measured shrub height (m) on 3 replicates of every species, and estimated the available biomass (%) on each stem in 1-m vertical increments from 0–6 m to reflect the range of moose winter browsing heights, depending on CRD snow pack conditions (T. Joyce, USDA Forest Service Cordova Ranger District, personal communication). We calculated the total available biomass (kg/ha; stem biomass × stem density) of every species in each plot.

To calculate moose utilization, we measured every instance of browsing (bite diameters) on the closest 0.5 m stem. We estimated biomass consumed (g/twig) with bite diameter-mass regression equations (MacCracken and Van Ballenberghe 1993) and summed the biomass removed per stem (g/stem). We collected nutritional samples of every browse species found at each plot, stored them fresh-frozen, removed all leaves, and sent them to the Washington State University Wildlife Habitat and Nutrition Lab (Pullman) for analysis.

We developed 3 winter scenarios (mild, moderate, and severe) by summarizing data on mean winter snow depth (cm) from 1917–2012 collected by the Alaska Climate Research Center (ACRC 2014) at Cordova's "Mudhole Smith" Airport weather station. We could not accurately model the interaction between snow depth, snow compaction, and biomass available within the moose browsing window (0.5–3.0 m without snow). Instead, we estimated the overall change in available biomass of browse in each plot according to our estimates of mean snow depth under each winter scenario, assuming that moose browsing height increased equally with snow depth.

To evaluate differences between treated sites and their controls, we used *t*-tests to compare individual browse species and total plot available biomass, height, crude protein, lignin, tannin, and utilization, as well as the ratio of willow:alder biomass. Individual willow species effects did not differ significantly and willow counts were pooled; feltleaf willow was not observed in any plot and was removed from analyses; the 1990–1992 treatments were analyzed as a single treatment because they were not documented separately. Furthermore, because we found few differences in time-since-treatment effects across stand types, we pooled all stand types for time-since-treatment analyses and used analysis of variance (ANOVA) to compare treatments across time and winter scenarios.

RESULTS

Treated willow, sweetgale, and total available biomass in 1990–1992 sites were higher than at control sites (P = 0.05, 0.003, and 0.001, respectively; Table 3) No other differences were found between treated and control sites in available biomass of any browse species or treatment year (Table 3). When weighted according to their untreated control (cut/control × 100), neither the relative total available biomass nor the relative total willow biomass differed significantly across times-since-treatment (Fig. 2). Treated alders in 2012 plots were shorter than in controls (P = 0.03). There was no significant effect on average willow height for time-since-treatment (Fig. 2), but the average treated willow was shorter than the average control willow (P = 0.003). There were no significant differences in nutritional quality

Table 3. Species-specific and total mean (±SD) available biomass (kg/ha), height (m), crude protein (%), lignin (%), tannin (mg/g), and use (%) of winter browse for moose in mechanically treated (cut, via hydraulic-ax) and untreated (control) sites on the Copper River Delta, Alaska, USA.

Browse Species	Age (yr)	Treatment	Biomass (kg/ha)	Height (m)	Crude Protein (%)	Lignin (%)	Tannin (mg/g)	Use (%)
Black cottonwood	1	Cut	10.89 (–)	1.0 (–)	[a]–	[a]–	[a]–	[a]–
		Control	2343.00 (–)	6.0 (–)	[a]–	[a]–	[a]–	[a]–
	3	Cut	[b]–	[b]–	[b]–	[b]–	[b]–	[b]–
		Control	[b]–	[b]–	[b]–	[b]–	[b]–	[b]–
	5	Cut	15.18 (11.05)	2.3 (1.2)	8.16 (2.56)	12.47 (0.65)	0.00 (0.00)	18.47 (0.32)
		Control	573.53 (522.92)	4.0 (2.8)	5.45 (–)	13.28 (–)	0.00 (0.00)	0.00 (0.00)
	23	Cut	[b]–	[b]–	[b]–	[b]–	[b]–	–
		Control	21.49 (51.19)	4.5 (2.1)	4.74 (–)	18.7 (–)	0.00 (–)	18.47 (–)
Sitka alder	1	Cut	18.15 (13.43)*	1.0 (0.0)**	[a]–	[a]–	[a]–	[a]–
		Control	605.42 (307.10)*	4.7 (1.2)**	[a]–	[a]–	[a]–	[a]–
	3	Cut	3.78 (4.99)	1.5 (0.7)	[c]7.64 (–)	[c]14.7 (–)	[c]31.6 (–)	57.05 (15.20)
		Control	138.59 (240.04)	6.0 (–)	[c]7.64 (–)	[c]14.7 (–)	[c]31.6 (–)	0.40 (–)
	5	Cut	[b]–	[b]–	[b]–	[b]–	[b]–	[b]–
		Control	125.48 (149.59)	4.0 (0.0)	7.64 (–)	14.7 (–)	31.6 (–)	0.00 (0.00)
	23	Cut	143.42 (430.25)	5.0 (–)	7.64 (–)	14.7 (–)	31.6 (–)	0.00 (–)
		Control	257.49 (429.99)	4.5 (1.29)	7.64 (–)	14.7 (–)	31.6 (–)	7.17 (12.41)
Willow spp.	1	Cut	78.13 (75.01)	1.3 (0.6)	[a]–	[a]–	[a]–	[a]–
		Control	279.81 (253.04)	3.9 (1.9)	[a]–	[a]–	[a]–	[a]–
	3	Cut	386.19 (416.60)	1.4 (0.5)	7.04 (0.71)	11.87 (0.48)*	49.07 (17.64)	14.50 (10.87)
		Control	405.41 (244.35)	2.3 (0.7)	6.91 (0.89)	15.47 (2.08)*	44.51 (19.55)	12.67 (5.03)
	5	Cut	550.79 (370.05)	1.6 (0.5)	7.91 (1.13)	15.53 (1.47)	32.28 (30.92)	3.25 (4.27)
		Control	260.67 (112.35)	3.7 (1.5)	6.85 (1.18)	13.71 (1.29)	43.52 (3.03)	0.00 (0.00)
	23	Cut	1225.01 (614.71)**	2.0 (0.5)	7.06 (0.54)	15.60 (1.67)	48.26 (16.92)	16.17 (15.45)
		Control	522.89 (408.90)**	2.5 (0.7)	7.07 (0.64)	15.61 (0.54)	37.48 (30.56)	11.83 (8.35)

Table 3 continued . . . .

Table 3 continued

Browse Species	Age (yr)	Treatment	Biomass (kg/ha)	Height (m)	Crude Protein (%)	Lignin (%)	Tannin (mg/g)	Use (%)
Sweetgale	1	Cut	21.06 (36.47)	1.0 (–)	[a]–	[a]–	[a]–	[a]–
		Control	0.04 (0.08)	1.0 (–)	[a]–	[a]–	[a]–	[a]–
	3	Cut	76.63 (86.54)	1.0 (0.0)	8.50 (0.64)	22.42 (0.86)	44.53 (1.33)	53.00 (23.07)
		Control	250.13 (221.49)	1.0 (0.0)	6.85 (–)	22.61 (–)	98.90 (–)	33.50 (21.92)
	5	Cut	403.28 (547.33)	1.0 (0.0)	6.75 (–)	17.00 (–)	41.00 (–)	10.80 (6.22)
		Control	[b]–	[b]–	[b]–	[b]–	[b]–	[b]–
	23	Cut	503.02 (560.63)**	1.0 (0.0)	7.53 (0.46)*	21.73 (0.59)*	56.98 (27.95)*	7.75 (8.18)
		Control	56.30 (103.77)**	1.0 (0.0)	6.91 (0.11)*	22.51 (0.17)*	95.37 (6.12)*	40.00 (40.15)
Total winter	1	Cut	120.96 (80.93)	1.17 (0.29)*	[a]–	[a]–	[a]–	[a]–
		Control	1666.26 (1292.39)	4.13 (1.63)*	[a]–	[a]–	[a]–	[a]–
	3	Cut	466.59 (476.44)	1.35 (0.47)	7.52 (0.27)	14.80 (1.27)	43.66 (6.70)	23.28 (12.00)
		Control	794.12 (212.15)	2.38 (1.19)	6.94 (0.80)	16.40 (2.53)	51.06 (23.13)	16.00 (15.09)
	5	Cut	969.24 (852.05)	1.76 (0.77)	8.13 (1.50)	14.47 (0.23)	23.79 (23.96)	5.00 (5.83)
		Control	959.69 (663.60)	3.44 (1.50)	6.81 (0.55)	14.13 (0.83)	30.43 (8.34)	0.00 (0.00)
	23	Cut	1871.44 (711.48)**	1.96 (0.56)*	7.19 (0.38)	16.77 (2.04)	46.76 (16.92)	10.67 (4.23)
		Control	858.17 (454.79)**	2.86 (1.01)*	7.06 (0.60)	16.20 (1.30)	40.75 (29.50)	9.33 (7.58)

Treated sites were sampled 1, 3, 5, or 23 years post-treatment (age) in 2012 & 2013.
[a]Re-growth of sites had not occurred by the time of spring nutritional sampling in one-year-old sites, but had occurred by the time of fall biomass sampling.
[b]Species did not occur in site.
[c]Alder samples combined for nutritional analysis.
**t*-test, P = 0.06–0.10 between cut and control.
***t*-test, $P \leq 0.05$ between cut and control.

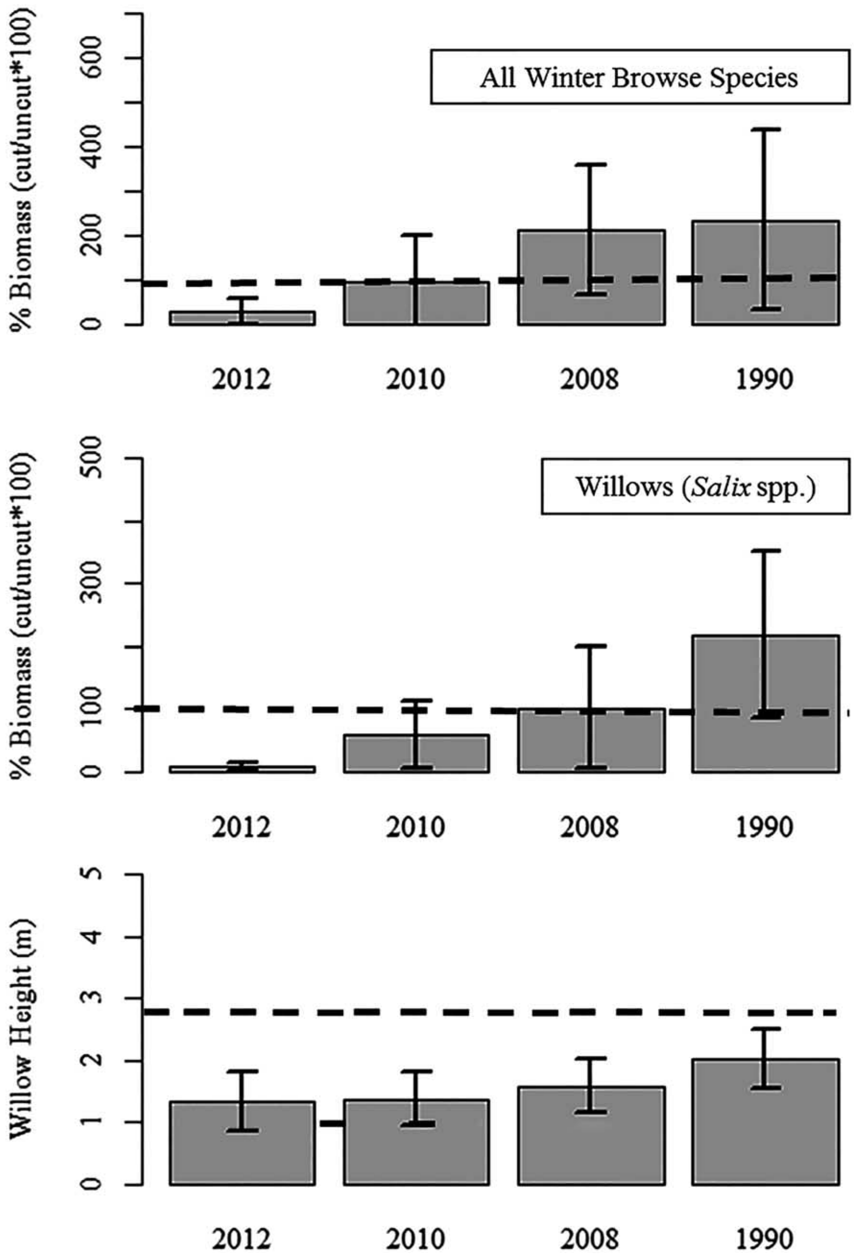


Fig. 2. Total relative biomass (cut/uncut × 100, ±SD) of all winter browse species, relative biomass of willows (*Salix* spp.), and mean heights of treated willows available to wintering moose within mechanically treated (via hydraulic-ax between 1990–2012) sites on the Copper River Delta, Alaska as of 2012–2013 sampling. The dashed line represents the point at which treated sites have recovered pre-treatment biomass (100%) or the mean height of untreated willows (2.85 m). Relative biomass across the 4 treatments was not significantly different ($P = 0.15$ and 0.13, respectively, 3 df). The average treated willow is significantly shorter than the average untreated willow ($P = 0.003$), but treated willow heights across treatment years are not significantly different ($P = 0.13$, 3 df).

or utilization across any comparison. The ratio of willow:alder in treated sites was higher than in control sites at 23 years post-treatment (treated = 1163.37, control = 205.82, P = 0.004), though treated sites 1, 3, and 5 years post-treatment were not different (treated = 11.26, 323.63, 550.79, respectively; control = 0.77, 360.11, and 74.38, respectively). All treatment years were different (P = 0.02, 3 df).

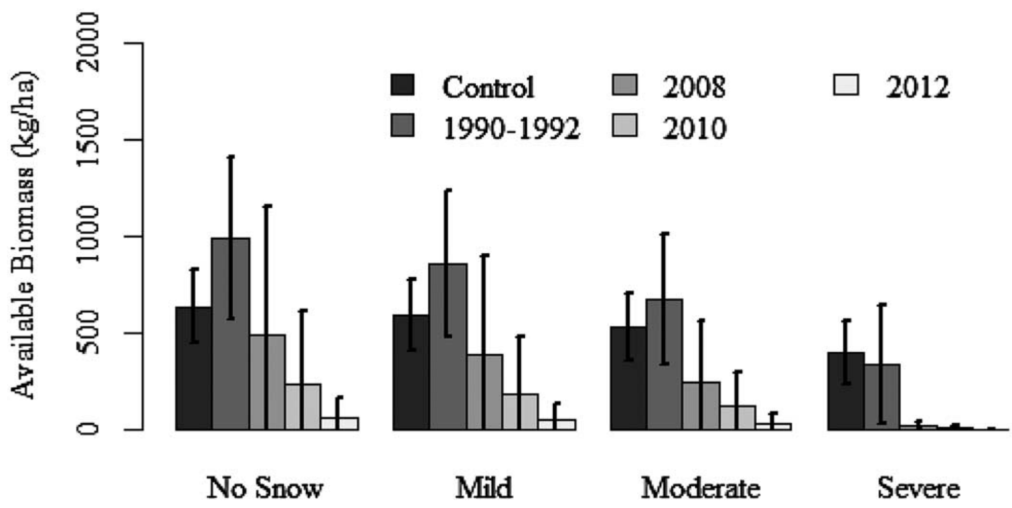
The 3 winter scenarios (mild, moderate, and severe) occurred 49, 29, and 11 times, respectively, with 6 winters uncategorized due to missing data. Mean snow depth differed by scenario; 11.4 cm (±9.9–12.9), 25.8 cm (±23.3–28.3), and 63.9 cm (±47.4–80.4), respectively. Total available biomass across times-since-treatment varied significantly by scenario (P = 0.007–0.03, 4 df; Fig. 3). Total available biomass in treated 1990–1992 plots also differed across scenarios (P = 0.04, 3 df), declining 61% from mild to severe winters. Further, available willow biomass across times-since-treatment varied significantly by scenario (P = 0.01–0.05, 4 df; Fig. 3). Treated willow biomass in the 2008 plot differed across scenarios (P = 0.05, 3 df), declining 95% from mild to severe winters.

DISCUSSION

Our data indicate that hydro-axing produces more total and willow biomass, with the effect increasing over time. Given the observed variability, our *a posteriori* power analyses suggested sample sizes of 9–17 would be necessary to detect significance in comparisons of willow-only or all-species browse; however, treatment caused significant increase in the ratio of willow:alder over time. Our results support those of Harrington (1984), and further suggest that hydro-axing can be an effective method to increase willow biomass and counter ecologically-initiated (including earthquake-influenced hydrological or successional) increases in alder. Hydro-axing did not influence the nutritional quality of the treated browse, as suggested by the lack of difference in crude protein, lignin, tannins, and utilization by moose. Bowyer et al. (2001) reported similar findings for treated feltleaf willow in interior Alaska, whereas Rea and Gillingham (2001) measured nutritional differences in Scouler's willow (*Salix scouleriana*); however, both studies were short-term (≤3 years post-treatment).

The high variability in height (m) of treated willows makes it difficult to determine if hydro-axing affects final regrowth height and the biomass available to moose across winter scenarios. Because the average treated willow is shorter, yet more productive than the average untreated willow, hydro-axing may be causing a bushier growth form in treated willows, with more biomass concentrated in many smaller shoots on recovering stems. A changed architecture may explain the larger decrease in available biomass relative to controls in 1990–1992 treated sites as winter severity and snow depth increased. However, after 23 years of regrowth, mean available biomass in severe winters was similar to the mean available biomass provided by controls, suggesting that overall availability of treated biomass may compensate for losses due to snow burial. If so, hydro-axing would be an effective tool for increasing biomass available to moose in mild and moderate winters, while maintaining "normal" availability in severe winters, given sufficient time for regrowth. Given the large gap between the 2008 and 1990–1992 treatments, we were unable to determine the regrowth asymptote or the minimal time required for winter browse species to recover sufficiently from treatment to provide equivalent (or potentially increased) biomass during severe winters.

Overall, our results indicate that mechanical treatment of moose winter browse



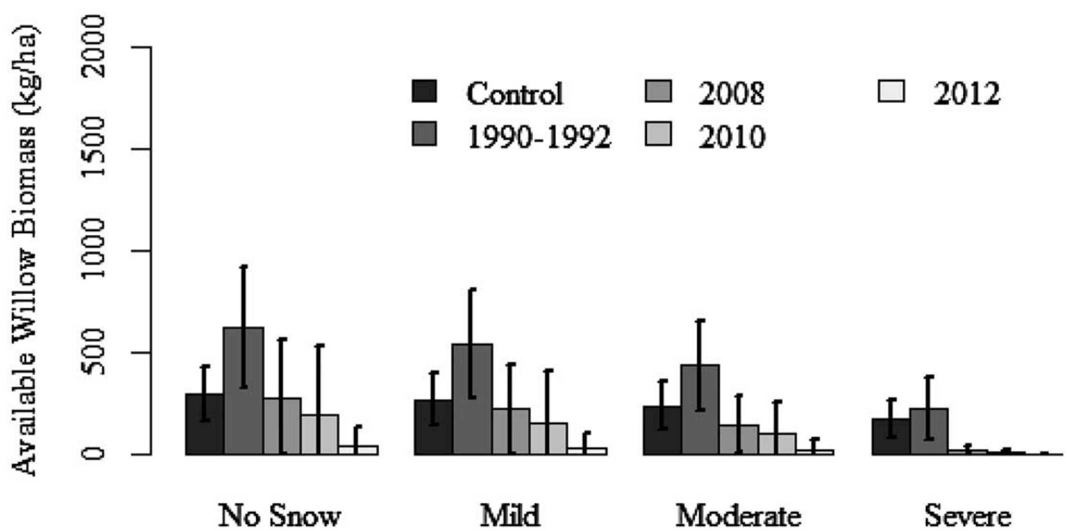


Fig. 3. Reductions in total and willow (*Salix* spp.) biomass (kg/ha, ±CI) available to moose due to mean snow depths in 3 winter scenarios (mild, moderate, severe) in mechanically treated (via hydraulic-ax) sites cut over 4 years (1990–1992, 2008, 2010, and 2012) on the Copper River Delta, Alaska. Sites were sampled in 2012–2013. All biomass differences within winter scenarios are significant (P = 0.007–0.03 and 0.01–0.05, respectively, 4 df), and the 1990–1992 across-scenario differences are significant (P = 0.04, 3 df).

species via hydro-axing has potential to reduce alder and increase willow biomass for wintering moose on the CRD. However, extensive treatment could limit browse availability during extreme winter scenarios (deep snow) until regrowth occurs in a few decades. Managers should be cautious in applying this technique across large areas concurrently. Furthermore, monitoring at more frequent intervals should determine the temporal development and long-term effects of mechanical treatment on moose forage in the CRD. This study provides a substantial summary of the effects of mechanical treatment on winter browse species, and should provide habitat managers of the CRD and similar areas with a useful structure for current management decisions and further research.

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